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Characterization of Resin-Coated Silica Sand from Tibawan Rokan Hulu For Potential Use as Proppant

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ABSTRACT - This study is aiming to evaluate the properties of quartz sand in Tibawan, Rokan Hulu, to determine its suitability as a proppant material for the oil and gas industries. The evaluation of these materials is being carried out based on the guidelines of American Petroleum Institute (API) 19C criteria, specifically assessing sphericity, roundness, bulk density, turbidity, acid solubility, and crush resistance. Furthermore, a surface modification process is being carried out where the sand is being coated with epoxy resin in three different weight variants (6 grams, 9 grams, and 12 grams) to investigate the effect of this treatment on the material's physical and mechanical characteristics. The test results are confirming that the sample covered with 12 grams of epoxy resin (Sample 4) is passing all API 19C specifications. In contrast, other samples are having weaknesses in one or more parameters being considered. The sample 4 is having a value of 0.62 roughness, 0.85 sphericity, 1 turbidity, 0.91 g/cm³ bulk density, 2.5 percentage acid soluble, and 6.05 percentage mass loss at a pressure of 7000 psi. These observations are indicating the potential of Tibawan quartz sand, modified by epoxy resin, as a non-conventional proppant that is being used in the hydraulic fracturing of upstream oil and gas activities.

Keywords: Tibawan, proppant, epoxy resin, quartz.

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INTRODUCTION

Proppant is pumped during hydraulic fracturing to maintain the openness of preexisting fractures, thereby enhancing the recovery and flow of hydrocarbons (Al-Muntasheri 2014). Quartz sand is a well-known proppant with the first successful application recorded in 1947. The material remains widely utilized in contemporary hydraulic fracturing operations (Liang et al. 2016). To date, proppant has been manufactured from materials such as walnut shells, natural sand, resin-coated sand, glass beads, sintered bauxite, kaolin, or fused zirconia. Among all these materials, quartz sand, characterized by high levels of silica, is the most widely used (Hamzah et al. 2021).

The functions of proppant in fracturing treatments are classified based on the material composition, mechanical strength, and morphological characteristics (Lam et al. 2019). Silica-rich mineral such as quartz sand is commonly selected as proppant materials in hydraulic fracturing due to the low cost, wide availability, ease of accessibility, and low specific gravity, making the materials effective in maintaining fracture conductivity during hydrocarbon extraction.

The most popular proppants are silica minerals and quartz sand because they have ideal characteristics, creating suitability and eligibility for application in hydraulic fracturing. Quartz sand, also called quartz mud sand, is spherical and has a high silica content (more than 98 percent), low density (less than 2.55), and high sphericity and roundness (greater than 0.6), making it an appropriate choice when performing hydraulic fracturing in shallower formations. These developments have increased the demand for quartz sand over the past few years, specifically in fracturing processes involved in the extraction of hydrocarbon deposits (Michael et al. 2020).

Silica minerals and quartz sand are unsuitable for deep wells due to their insufficient strength to withstand high closure pressures exceeding 35 MPa. If proppant strength does not align with formation closure pressure conditions, it can break into fine fragments, significantly impairing fracture conductivity (Bestaoui-spurr 2014). Fracture conductivity is influenced by factors such as proppant size, backflow occurrences, and fine generation (Watanabe 2009). Several parameters contribute to reduced fracture conductivity, including fine migration (Michael et al. 2020), proppant diagenesis, proppant crushing, and proppant deposition (Pasarai et al. 2010).

To overcome these limitations mentioned above, the use of ceramic proppant has been adopted in hydraulic fracturing operations (Bestaoui-spurr 2014). Ceramic proppant is more conductive than quartz sand at the same pressure and proppant layer thickness due to better resistance to crushing and chemical degradation (Zoback & Kohli 2019). However, ceramic proppant costs three to five times more than proppant quartz sand (Katende et al. 2021). Moreover, the high density of ceramic proppant necessitates the use of fracturing fluids with elevated flow rates and viscosity to ensure effective transport into subsurface fractures. Inadequate fluid support may result in premature settling near the fracture entrance, limiting penetration to the deeper sections (Maity & Ciezobka 2019).

Natural proppant has both low density and high resistance to being crushed. It may be modified by coating with resin, epoxy resin, or fiber. Resin-coated proppant has a range of densities in 1.25-2.61, and a mixture capable of withstanding the closure pressure at 10,000 to 15,000 psi. Proppant selection and analysis are critical components of hydraulic fracturing, ensuring that the selected material is compatible with the reservoir's production conditions and operational requirements. API 19C requires that proppant roundness and sphericity, acid solubility, bulk density, turbidity, and crush resistance be considered to determine the quality (Zoveidavianpoor & Gharibi 2015).

Roundness refers to the smoothness and lack of angularity of a proppant particle, while sphericity indicates how closely the particle's shape approximates that of a perfect sphere. These attributes play an important role in defining compressive strength and the mechanical stability of a proppant. Balanced and spherical proppants have better structures and would not break easily under tension, while angular or broken ones will break easily. Roundness and sphericity are tested according to the guidelines of API 19C standards. Furthermore, the Krumbein shape factor is an acceptable feature with a recommended minimum of 0.6 to 0.7. These qualities have a significant effect on grain packing and fracture permeability, where well-rounded proppant obtained greater fracture permeability as compared to angular or irregular ones (Edition et al. 2008). Studies on proppant in the Mahu tight conglomerate reservoir indicate that the size significantly influences content and mass ratio. The retention rate of proppant in the 40/70 mesh size is higher than that of the 20/40 mesh (Tang et al. 2018).

Bulk density is defined as the mass of the loose proppant per unit volume. This is determined by filling a volume of a specific amount and measuring the weight according to the guidelines of API 19C processes (Wang et al. 2024). Acid solubility is also an important measure of chemical stability, considering that proppant can also degrade in the presence of HCl and HF acids, which are used in clean-up formations, and can lead to loss of structural integrity (Edition et al. 2008). Solubility indicates the material that can be dissolved, such as carbonates, clays, and ferrous oxides. In the meantime, turbidity measures the number of fines; high turbidity indicates a large number of impurities that may plug the conduction of the fracture.

The crush resistance is an important parameter in proppant analysis, as it determines the pressure the material can withstand and the structural integrity under high-stress conditions. The existence of fines has a high adverse effect on reducing the wells' permeability and production efficiency because the fines can fill pores, hence the reduction in the wells' permeability and production efficiency. According to the studies, the amount of fine-grain concentration dropping down to less than a 5% level can cut more than half of proppant conductivity, emphasizing the significance of proppant choice with an ideal strength quality (Tang et al. 2018).

Various researchers are examining the feasibility of applying quartz sand material from different regions as a proppant in hydraulic fracturing. The study, which combined two types of proppant, Ottawa Proppant and Mississippi Proppant, reported that samples weighing 300 grams managed to withstand a pressure of 4000 psi. Furthermore, the proportion of crushed sand grains was maintained at 5.80, which does not reach the maximum limit of the API 19C standards. This result shows that the sample can be used as a proppant in hydraulic fracturing procedures.

According to Lam et al. (2019), natural silica samples were collected from various locations along the Red Sea coast, Sinai, and the Eastern Desert. Based on crush resistance testing, both samples exhibited excellent mechanical strength. The study suggested that quartz sand from this region is highly suitable for use as a proppant in hydraulic fracturing applications. In a study involving three specimens, one consisted of ceramic proppant, while the other two samples were silica minerals obtained in Tampin and Meraga Villages in Malaysia. Experimental results showed that fluid-free sand with a fines content of less than 10% can only withstand a hard pressure of 2250 psi, meaning Sample 1 can be used in fracture treatment (Gaber & Gamal El-Din A. Ibrahim 2021). The use of organic thermosetting and thermoplastic polymers, epoxy, PS, PHEA, and PP propellants, has been explored in terms of propellant development. Composite fillers (e.g., carbon nanotubes (CNTs), clay, nanosilica, graphene) should also be added to these polymers to improve the performance properties (Kamat et al. 2011).

Natural silica minerals are widely distributed across various regions of Indonesia, presenting a promising opportunity for the local production of proppant materials (Zoveidavianpoor & Gharibi 2015). Some interesting sources include spots in Rokan Hulu and Rupat Island of Bengkalis Regency, Riau Province, and Tuban in East Java. The possibility of local Indonesian quartz sand being used in hydraulic fracturing has also been observed during the previous study (Rpc et al. 2024)

This study presents a specific investigation on quartz sand samples collected in the Tibawan region of Rokan Hulu Regency in Riau. The aim is to analyze whether Tibawan quartz sand can be a proppant based on experimental tests according to the standards of API 19C. Furthermore, this study also examines the impact of varying amounts of epoxy resin coatings, specifically 6 grams, 9 grams, and 12 grams, on key proppant properties, including roundness and sphericity, acid solubility, bulk density, turbidity, and crush resistance.

METHODOLOGY

The primary materials used were quartz sand obtained from Tibawan in Rokan Hulu. An initial evaluation of Tibawan quartz sand was carried out to assess its viability as a proppant. This assessment was carried out according to the criteria established in the API 19C standard, concentrating on several key parameters. These parameters were systematically analyzed to ascertain the materials' suitability for use in hydraulic fracturing operations. The evaluation of natural sand as a potential proppant requires thorough testing of parameters such as roundness and sphericity, bulk density, acid solubility, turbidity, and crush resistance, all of which must comply with API 19C standards to ensure its suitability for hydraulic fracturing applications (Rpc et al. 2024).

A grain size distribution test was conducted

Table 1. API 19C specification

No	Analysis	Standard API 19C
1	Roundness Sphericity	0,6
2	Bulk Density	>1,5 gr/cc
3	Turbidity	<250 NTU
4	Acid Solubility	< 3%
5	Crush Resistance	<10%

before analyzing roundness and sphericity, acid solubility, bulk density, turbidity, and crush resistance of quartz sand samples.

This process involved preparing 100 grams of quartz sand, which was sieved using a 40/70 mesh. The general composition of quartz sand is presented as follows:

Table 2. Chemical composition of quartz sand

Composition	Percentage (%)
C	8.36
Na_2O	4.25
Al_2O_3	0.34
SiO_2	86.93
CaO	0.12

After the sieving process, the subsequent testing phase evaluated several key parameters such as roundness and sphericity, acid solubility, bulk density, turbidity, and crush resistance.

The materials used in this testing phase included quartz sand from Tibawan, epoxy resin, distilled water (aquadest), and hydrochloric acid (HCl). The eequipment used for these tests is listed in figure 1 and the samples that will be tested in this study are listed in Tabel 3.

Table 3. Research sample

No	Sample	Parameter
1	Sample 1 (S1)	Tibawan Quartz Sand
2	Sample 2 (S2)	Tibawan Quartz Sand + 6 grams of epoxy resin
3	Sample 3 (S3)	Tibawan Quartz Sand + 9 grams of epoxy resin
4	Sample 4 (S4)	Tibawan Quartz Sand + 12 grams of epoxy resin

The job analysis process is illustrated in the workflow shown in Figure 1. Roundness and sphericity assessment begins with weighing 5 grams of quartz sand and placing it on a sample container. Sand grains were examined under a microscope with a magnification range of 10x to 40x. Subsequently, 20 grains were randomly selected from each sample and evaluated for roundness and sphericity using the Krumbein Shape Chart, as presented in Figure 2. The average values were calculated by the procedures outlined in ISO 13503-2:2006 and API 19C.

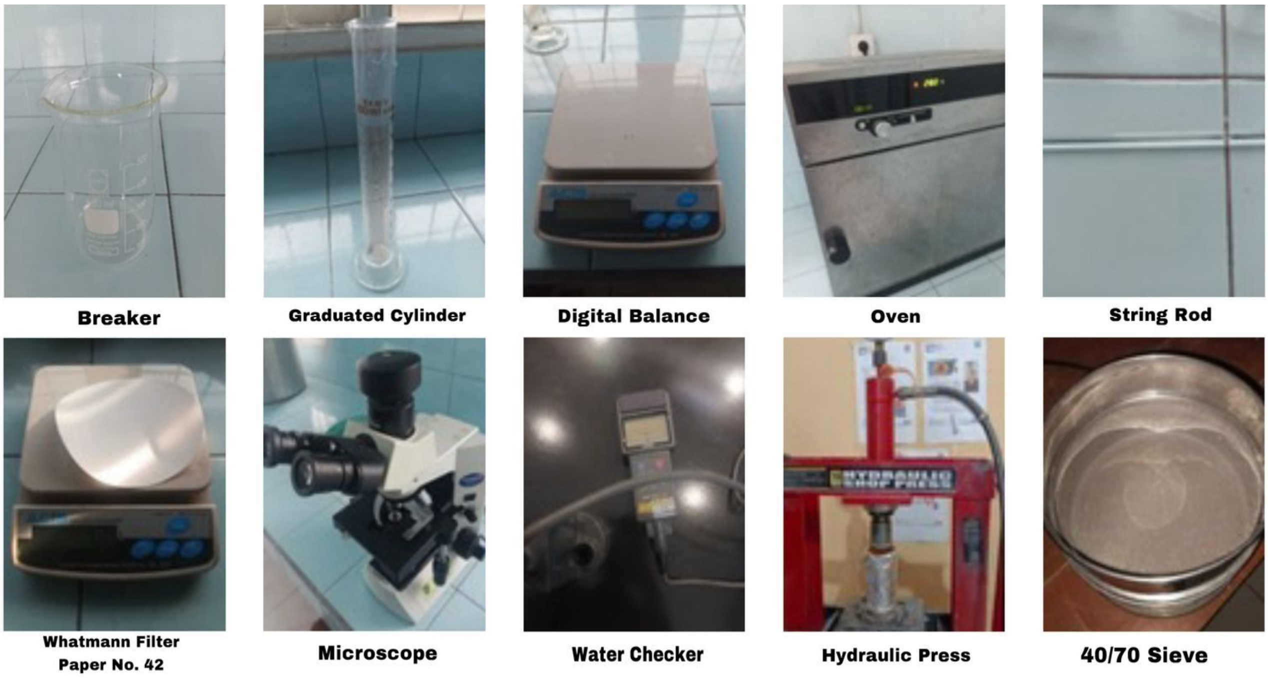

Figure 1. Equipment

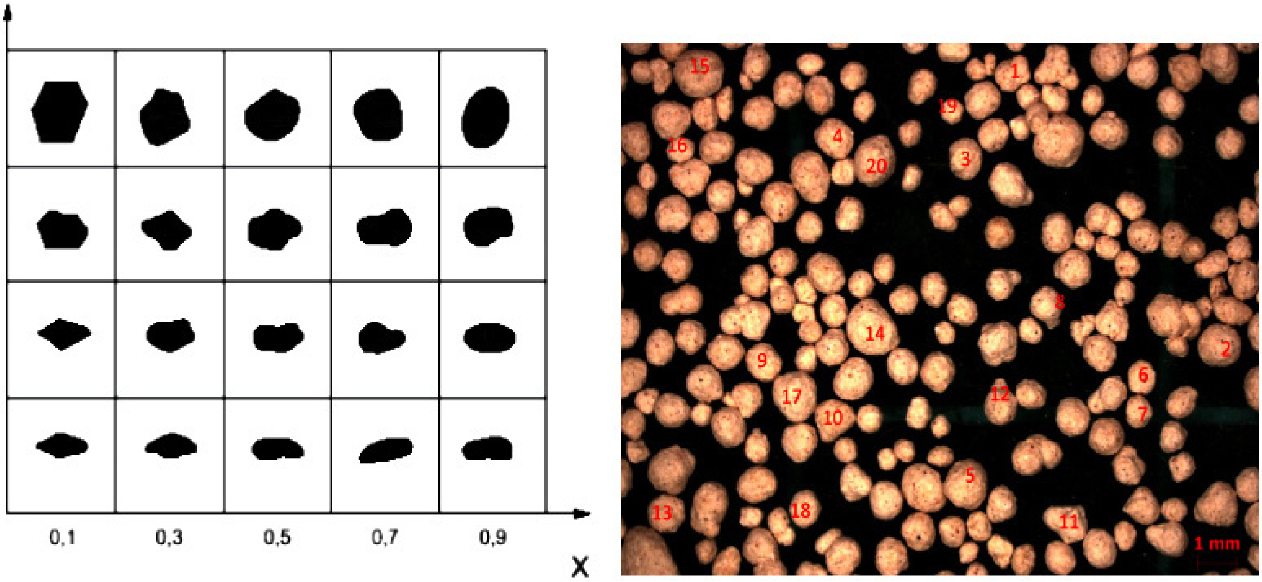

Figure 2. Krumbain Shape Factor test showing the reference chart for roundness and sphericity (left) and microscopic images of sand grain samples with labeling for shape evaluation (right)

Bulk density assessment was performed using a 100 mL measuring cylinder, a digital scale, and quartz sand samples from Tibawan. The proppant chemical stability under acidic conditions resembles downhole environments, was evaluated with acid solubility tests. For proppant samples, a concentration of 12% hydrochloric acid and 3% hydrofluoric acid was mixed to prepare a testing solution simulating possible exposure during hydraulic fracturing. The proppant sample was 25 grams of quartz sand in a beaker. W1 was the sample's weight prior to testing. To ensure proppant reaction with the acid was regulated, the sample was submerged in 100 mL of the previously made acid solution. This approach allows for accurate measurement of proppant degradation, and critical information about proppant compatibility with acidic fluids is obtained. The result helps determine appropriate proppant materials for effective reservoir stimulation and maintaining long-term fracture conductivity in oil and gas extraction.

Proppant crush resistance was assessed with a hydraulic press and crush cell device to evaluate the integrity under step stress conditions that simulated downhole environments. The crush resistance limits for different types of proppant were determined based on API 19C, a standard for estimating the performance of proppant used in hydraulic fracturing. Material selection was optimized to assist in the conductivity and stimulation of the reservoir in oil and gas extraction processes.

Table 4 shows the values for standardized crush resistance adherence with API 19C. These values are essential to determine the mechanical strength of proppant subjected to compressive forces during hydraulic fracturing. Following API 19C specifications guarantees the most suitable proppant will be selected, resulting in enhanced well and fracture conductivity in hydrocarbon extraction processes.

Table 4. Crush resistance specification API 19C

Proppant Type	Minimum Crush Stress MPa (Psi)
Hydraulic Fracturing	
Man-made proppant	34.5 (5000)
Natural sand proppant	13.5 (2000)
Gravel Packing	
Natural sand proppant	13.8 (2000)

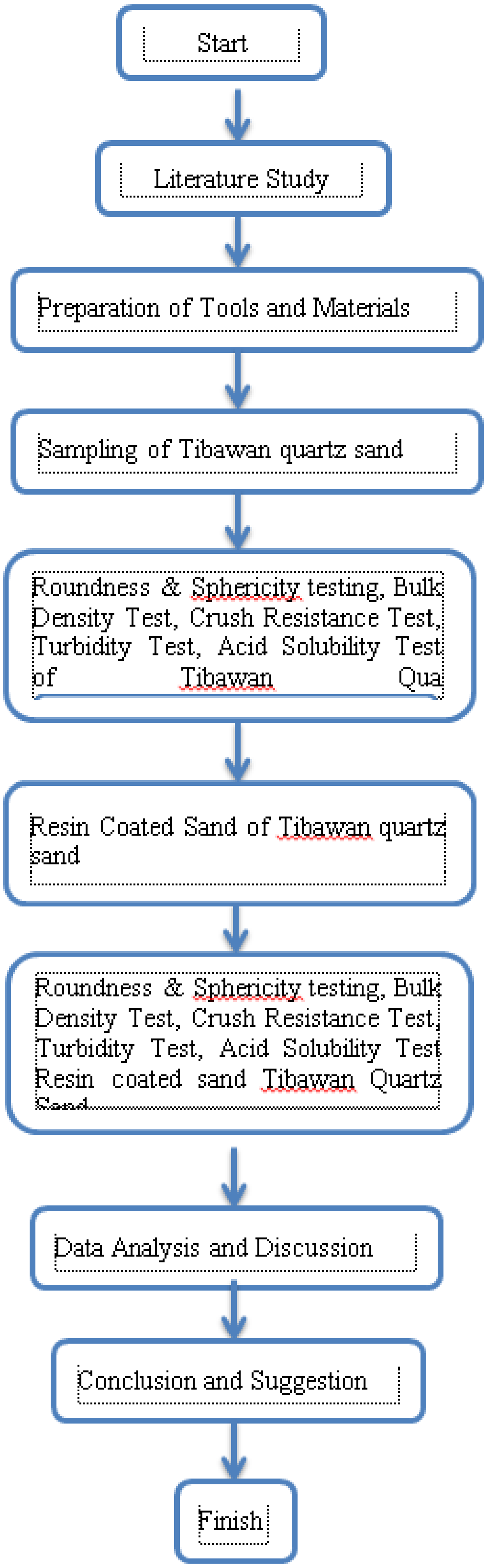

Figure 3. Flowchart of research methodology

The first step in the coating process is to weigh 100 grams of quartz sand and divide it among three containers. Subsequently, 6, 9, and 12 grams of epoxy resin are added to each container, guaranteeing differences in coating thickness for comparison. The mixtures are thoroughly stirred to achieve uniform distribution before drying or oven-curing until fully set and hardened. The coated quartz sand is gently ground with a pounder and sieved through a 40/70 mesh screen to achieve uniform particle sizing. This method aids in optimizing proppant selection for enhanced fracture conductivity and reservoir stimulation efficiency in oil and gas extraction workflows by enabling a controlled evaluation of the impact of resin coating on proppant durability, acid resistance, and structural integrity.

RESULT AND DISCUSSION

Roundness and sphericity

Roundness and sphericity are two important hydraulic fracturing parameters that directly affect how well proppant particles maintain fracture conductivity. Proppant with higher sphericity and roundness demonstrated superior crush resistance, enhancing both fracture support and the efficiency of oil and gas flow. In this study, 20 quartz grains from each sample were systematically analyzed for sphericity and roundness. Detailed information on proppant selection for hydraulic fracturing is given, and the results are provided (including distribution patterns and photographic data) for samples 1, 2, 3, and 4. Injectivity can be increased and reservoir rebuilding improved by enhancing proppant shape features to maximize hydrocarbon recovery.

Sample 1

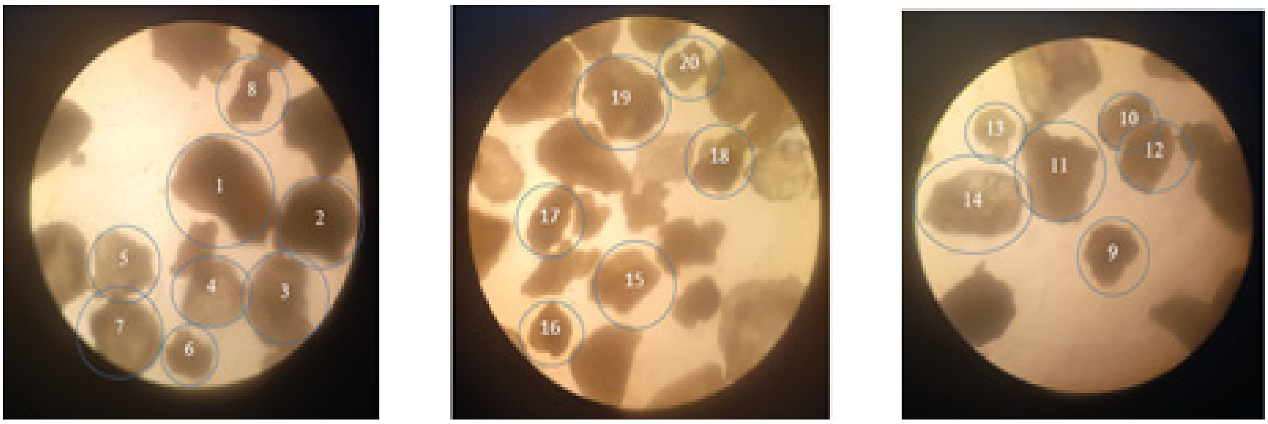

Figure 4. Roundness and sphericity test photo sample

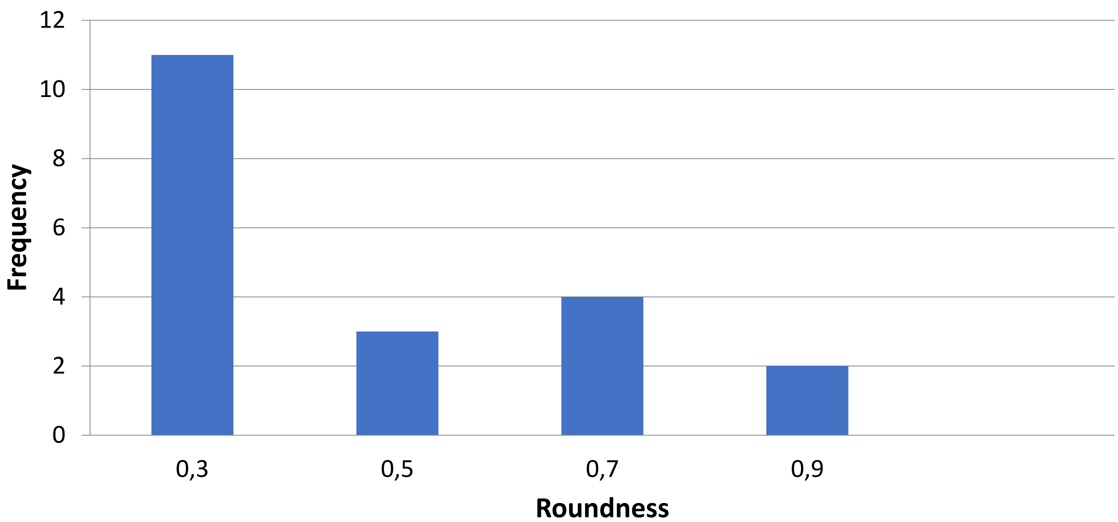

Figure 5. Distribution roundness and sphericity sample 1.

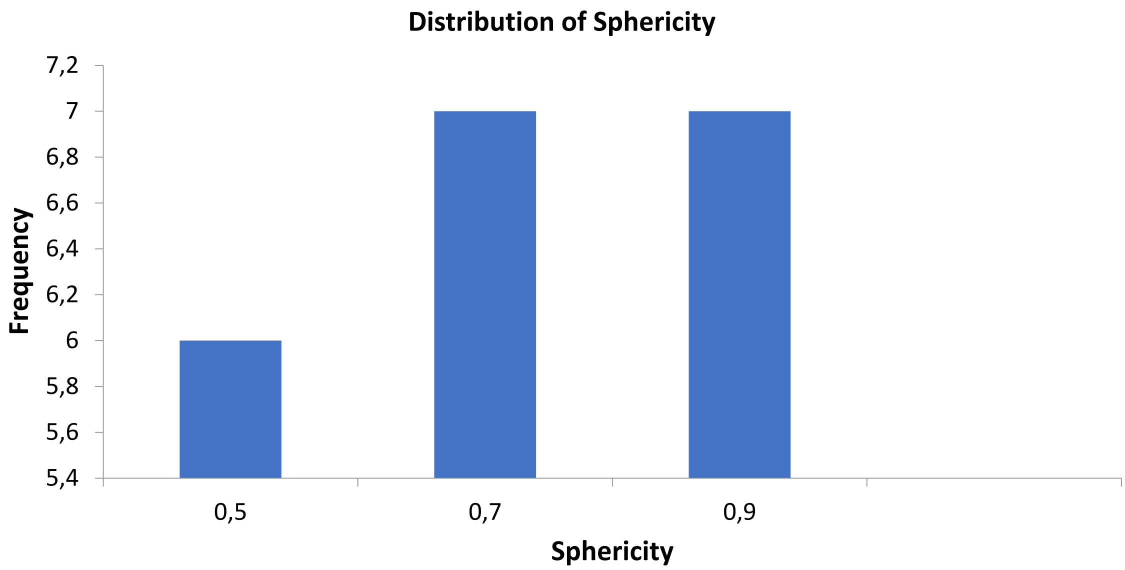

Figure 5. Distribution roundness and sphericity of sample 1 (continued)

Proppant sample analysis showed a roundness between 0.3 and 0.9 and a sphericity given by this range. An average roundness of 0.47 suggests that most proppants are of sub-angular to sub-rounded forms. In contrast, the average sphericity of 0.70 indicates a well-ingestible 3D geometrical shape.

In line with the industry benchmarks outlined by API RP 56 and API RP 60, premium-quality proppant must exhibit a minimum roundness and sphericity of 0.6. The results show that most of the samples analyzed fail to meet these thresholds, particularly regarding roundness. Proppant with roundness less than ideal (samples 4–10 and 19–20) is expected to have more friction for transporting in water and injection, and is anticipated to have more breakdown under pressure. On the other hand, samples with roundness greater than 0.6, i.e., samples 2 and 3, are expected to possess better mechanical durability and hydraulic performance. Sphericity distribution is clustered in a relatively narrow range near the average of 0.7, which denotes the average three-dimensional grain shape.

Detailed observation using a microscope showed remarkable heterogeneity in particle shape. High roundness and sphericity in some grains may indicate strong mechanical stability. However, non-spherical particles indicate potential mechanical weaknesses under compressive stress.

Sample 2

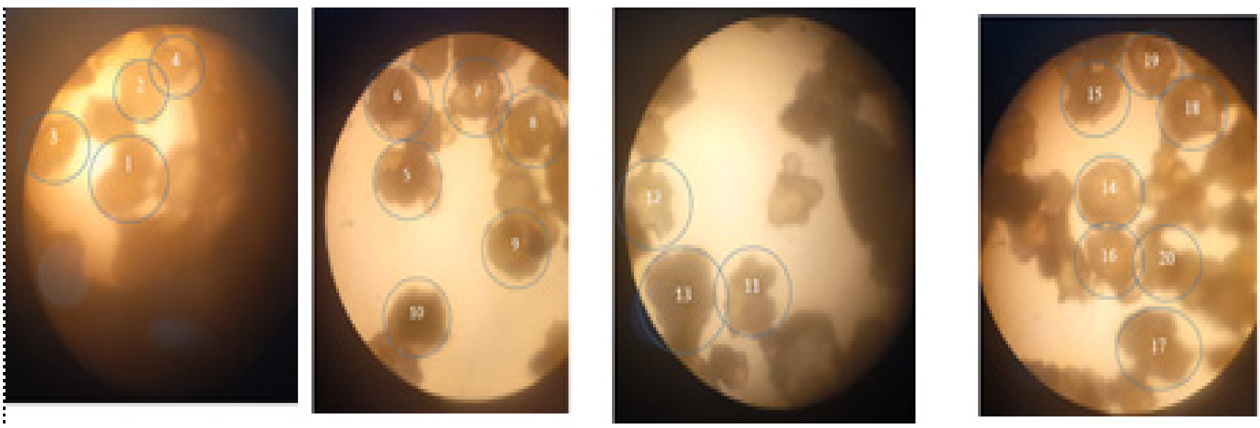

Figure 6. Roundness and sphericity test photo of sample 2

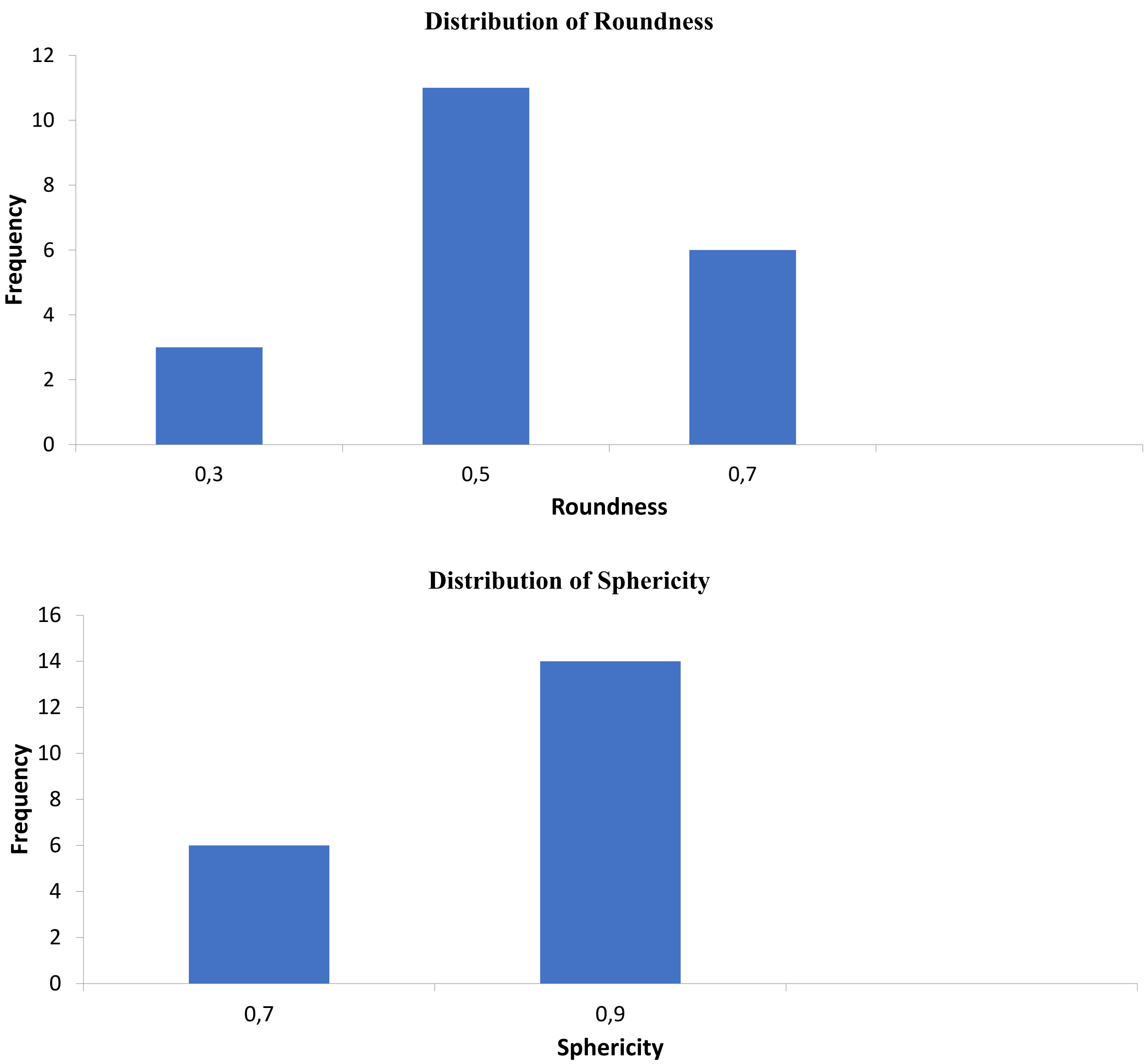

Figure 7. Distribution roundness and sphericity of sample 2

The dataset has roundness values between 0.3 and 0.7, with an average of 0.53. As per the recommendations of API 19C, the greater the roundness value, the better because it minimizes local stress concentration that can cause particle failure at elevated closure stress

The particles having roundness < 0.3, such as those in samples 3, 11, and 12, have angular or irregular shapes that deviate sharply from the ideal proppant geometry. These asperities enhance stress concentration factors at the contact between particles, which increases the potential for mechanical degradation, or breakage, under the high closure stresses commonly found in subsurface conditions. Approximately 60% of both particle data have a roundness of approximately 0.5, indicating the two fall in an intermediary class of samples. While such particles may perform satisfactorily in specific hydraulic fracturing scenarios, the particle shape might not adhere to the rigorous mechanical adequacy requirement in the API 19C. Therefore, more grading or surface processes are necessary to enhance the suitability of proppant in high-pressure regions.

Particles with roundness equal to 0.7, i.e., samples 1 and 5-10, generally have morphology characteristics that comply with the specifications specified in API 19C for proppant. This would have higher resistance to mechanical wear and degradation, and would be a good candidate as high-performance proppant in harsh reservoir conditions (American Petroluem institute 2008).

The observed sphericity values vary between 0.7 and 0.9, with a strong peak of approximately 0.9. This distribution causes a large average sphericity of 0.84, indicating the predominance of almost spherical particles in the collection. Approximately 85% of the samples show sphericity values in the range of 0.9, which means a very tightly packed particle population. This shape imparts to proppant good flowability and allows for a satisfactory packing degree, which is essential to preserve the permeability of the proppant pack, and reduce the quantity of void between proppant particles in the pack under down-hole conditions. High sphericity also enhances proppant transport and placement to minimize screenouts and enhance fracture conductivity. Conversely, samples 1, 3, 15-17, and 20 (sphericity = 0.7) remain an example of less favorable morphology, which may be deleterious to proppant pack quality. These particles have a greater chance of forming a complex packing structure, which might result in proppant bridging, different local heterogeneous distribution, and blockage zone occurring in the fracture network during the HF process (Duenckel et al. 2017).

Sample 3

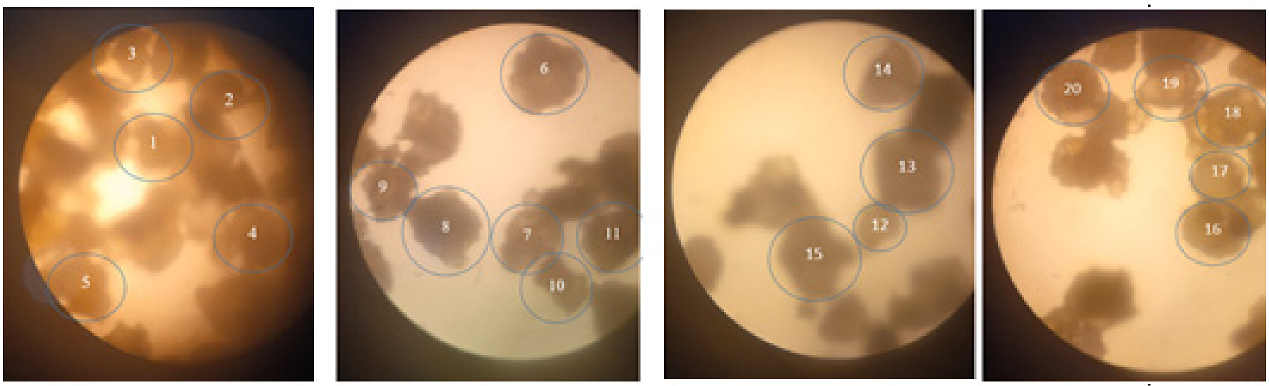

Figure 8. Roundness and sphericity test photo sample 3

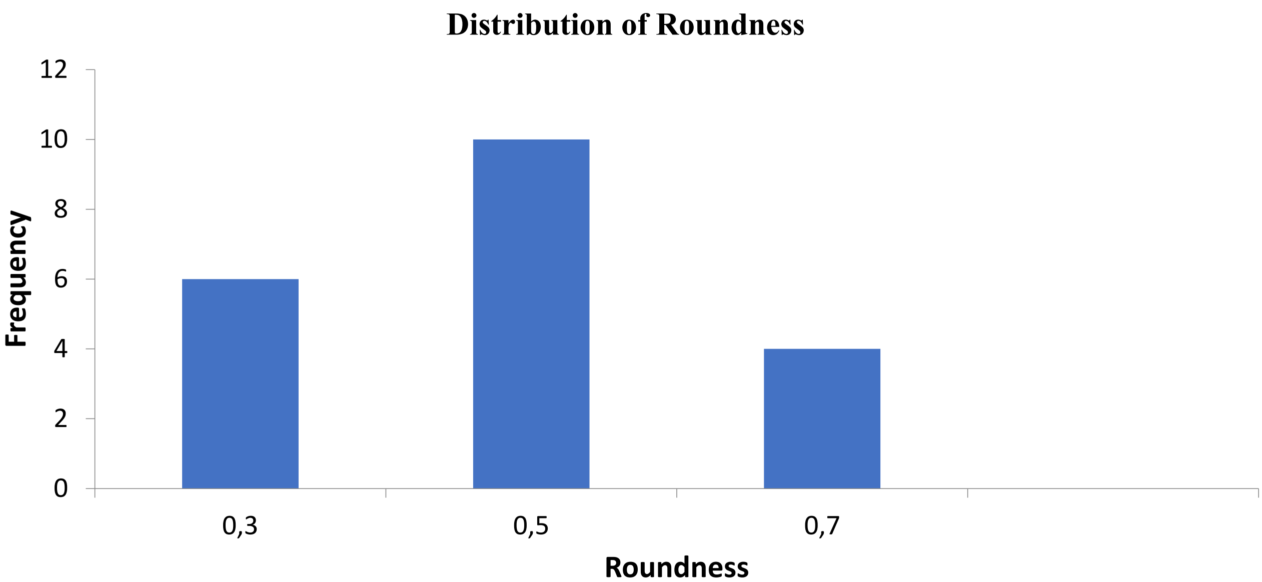

Figure 9. Distribution roundness and sphericity of sample 3

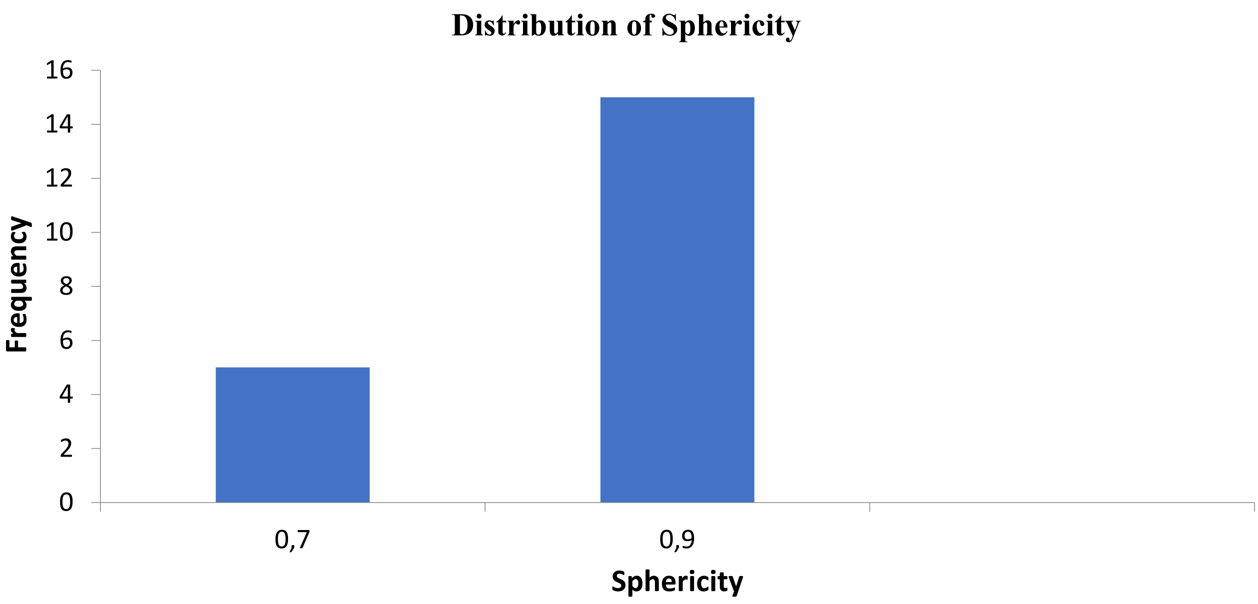

Figure 9. Distribution roundness and sphericity of sample 3 (continued)

The examination of roundness shows an average of 0.48, with a span of 0.3 to 0.7. These values are lower than the commercial proppant roundness benchmark of 0.6 provided by API 19C. The difference is consistent with previous results, which indicate that grain reorganization and pore channel blockage caused by irregularly shaped proppant significantly reduce fracture conductivity. Furthermore, only 25% of the sample population (5 out of 20) complied with API criteria. The other 75% were lacking in sufficient roundness, mainly characterized by angular or irregular edges, which are known to contribute to low fracture permeability and high proppant embedment greatly (Ding et al. 2020).

Sphericity measurements, on the other hand, were between 0.5 and 0.9, averaging 0.84; thereby, exceeding the minimum requirements set by API standards. Notably, 85% of samples reached the target sphericity of 0.9. (Xu et al. 2022) reported that highly spherical particles significantly improve pack porosity and fluid flow.

Sample 4

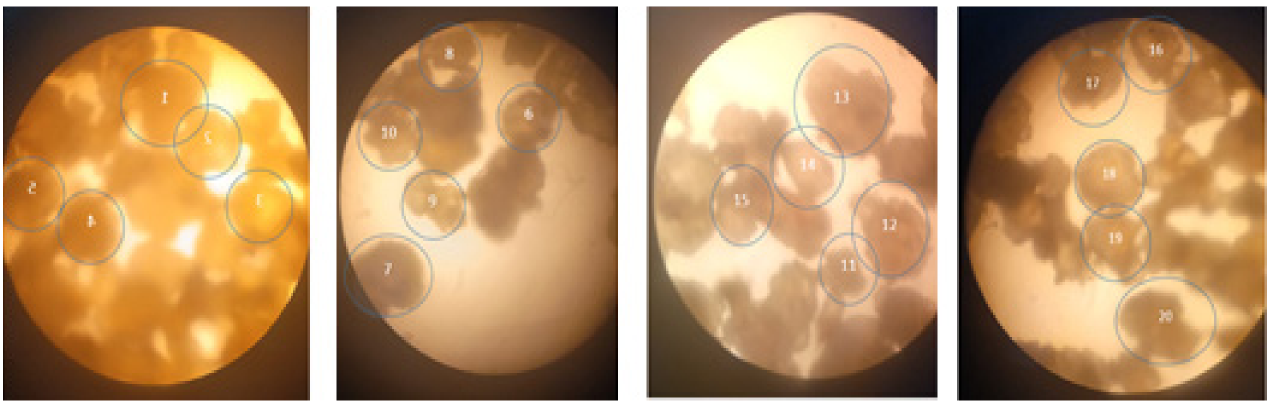

Figure 10. Roundness and sphericity test photo of sample 4

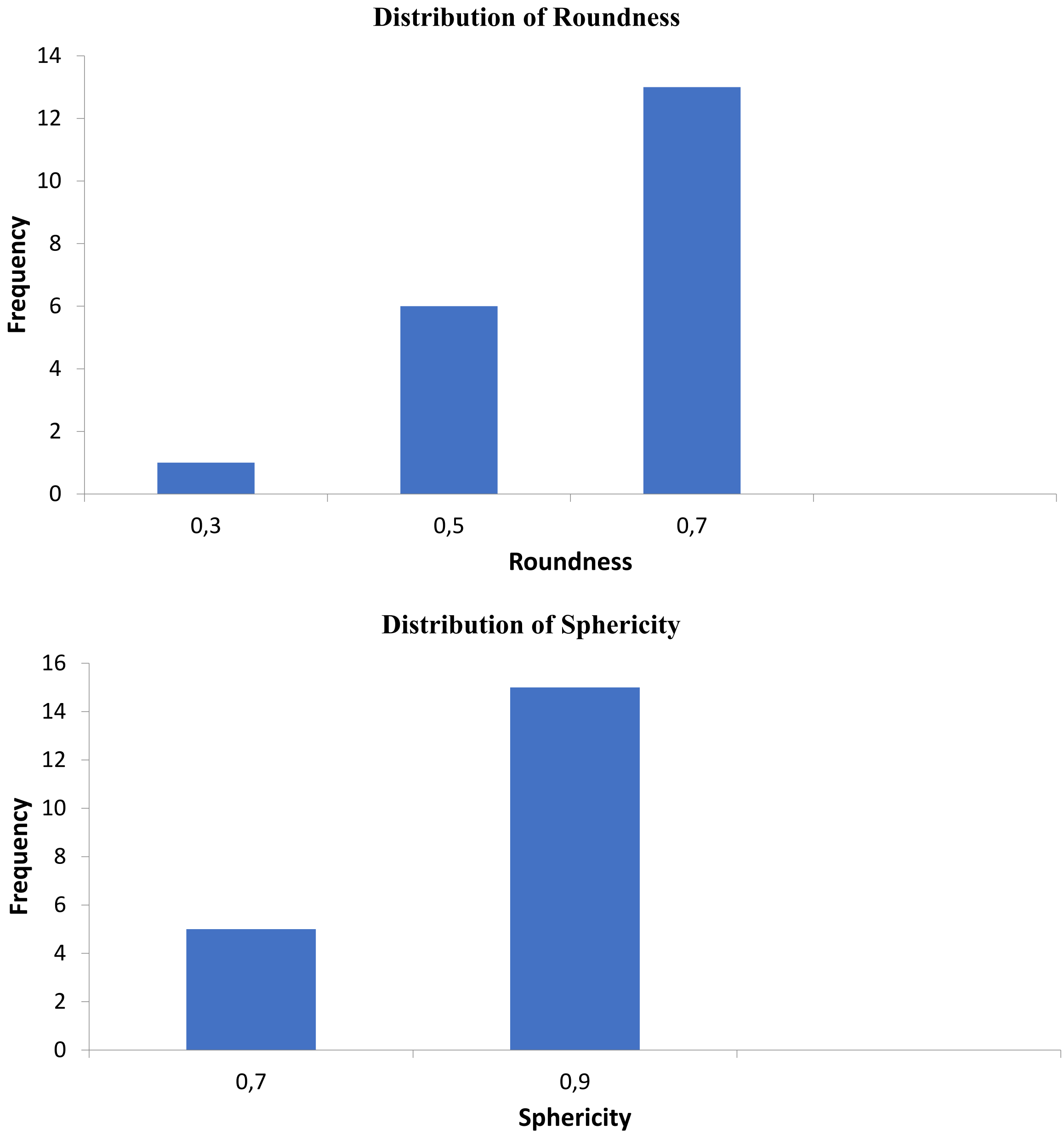

Figure 11. Distribution roundness and sphericity sample 4

For the 20 selected particles, roundness values ranged from 0.3 to 0.7, and sphericity values were 0.7 to 0.9. Notably, 65% of the samples exhibited a roundness value of 0.7, indicating adequate rounding that supports effective particle packing, improved flow dynamics, and overall proppant performance. Moreover, 70% of the particles had a sphericity of 0.9, indicating a substantial conformity to spherical shape. This is critical for uniform stress transfer during closure and reduced chances of fracture due to internal pressure. All these are important for the stability and effectiveness of proppant in hydrocarbon extraction. Based on the morphology parameters of great proppant applied in the petroleum industry, this study found that roundness and sphericity modal values were 0.7 and 0.9, respectively. However, certain deviations from the ideal values were also noticed. Persistent deviations concern Sample 11, which is highly angular and irregular in terms of particle shape as it has the lowest roundness of 0.3 and the lowest sphericity of 0.7. If these geometrical properties are excessively high in a proppant pack, they can negatively affect mechanical stability, particularly under increasing closure pressures. Elevated closure pressure is crucial for minimizing material crushing and permeability loss, as previously reported by Mehmood et al. (2022).

According to the criteria of API 19C, roundness and sphericity value should be greater than or equal to 0.6 to ensure that proppant can deliver under the operational pressures. With this criterion, a percentage (95) of the particles appraised in this study fulfilled the requisite morphological requirement, and therefore, the batch is made mainly of proppant that has desirable hydraulic and mechanical characteristics.

The morphological defects, including samples 11 and 14 that either lacked roundness or sphericity, may be detrimental to the integrity of the entire proppant pack. These non-uniform substances can become concentration points of stress, destabilize the ability of the proppant bed, and disturb the uniformity during the packing of proppant. The deviations may cause conductivity to reduce locally, thereby limiting the efficiency of hydrocarbon production in fractured reservoirs (Mollanouri-Shamsi et al. 2018).

The values of the average roundness and sphericity of the four samples are shown as follows:

Table 5. Roundness and sphericity average

Sphericity Test Results		
No	**Sample**	**Value**
1	S1	0.7
2	S2	0.84
3	S3	0.84
4	S4	0.85

Determining the squared roundness values of the four samples of the tested proppant, as shown in Table 5 and Figure 11, resulted in a varying range of 0.47 and 0.62. Particularly, samples S1 (0.47), S2 (0.53), and S3 (0.48) had roundness values lower than the recommended standards of the API. However, only sample S4 had a value of 0.62, which was within the required standards of API as per roundness. This shows that most proppants that have been examined (75%) do not have an optimal roundness and will be mainly angular or irregular in shape. Irregular or non-round proppants present several operational challenges, including increased susceptibility to mechanical failure under closure stress, a tendency to become lodged in the formation matrix, and a gradual decline in fracture conductivity over time, as outlined in API 19C. Conversely, all the sample measures were good with sphericity values between 0.70 and 0.85. The sample values were significantly higher than the API minimum of 0.6, and the sphericity average was 0.8075. The sample percentage with the largest sphericity (0.85) was S4, while samples S2 and S3 had sphericities of 0.84 each. The high departing sphericity is significantly important to improve the uniformity of proppant packing, reduce the stress concentration, and establish better fluid penetration through the proppant pack (Lu et al. 2022). These desirable sphericity results mean that the manufacturing routine was able to adequately control particle symmetry to a favorable morphology that allows the pack to preserve high fracture conductivity.

Table 6. Roundness test results

Roundness Test Results		
No	**Sample**	**Value**
1	S1	0.47
2	S2	0.53
3	S3	0.48
4	S4	0.62

The differences between roundness and sphericity significantly highlight an area that needs improvement. Although the particles exhibited excellent sphericity, their low roundness poses a risk to mechanical stability during hydraulic fracturing operations. Improving roundness, either through the optimized selection of raw materials or the development of more effective crushing and sieving techniques, is essential for achieving full API compliance and ensuring the reliability of proppant under high-stress downhole conditions. More studies should focus on improving the manufacturing methodologies, thereby creating a good balance between roundness. Sphericity may be achieved to enhance the overall performance of proppant materials in complex oil and gas reservoirs.

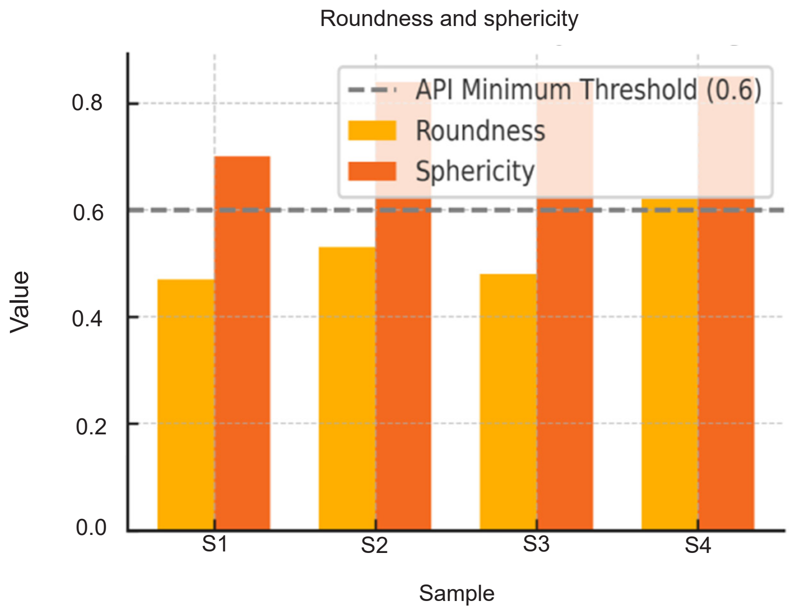

Figure 12. Comparison of average roundness and sphericity of Sample 1, Sample 2, Sample 3, and Sample 4

Bulk density test

Based on the study that has been conducted, the following bulk density values were obtained:

Table 7. Bulk density test results

Bulk Density Test Results			
No	Sample	Mark	unit
1	S1	1.1	gr/cc
2	S2	1.01	gr/cc
3	S3	0.97	gr/cc
4	S4	0.91	gr/cc

Table 5 shows that the bulk density of the proppant sample tested ranged between 0.91 gr/cc and 1.10 g/cc. The highest bulk density of 1.10 g/cc was recorded in sample S1, indicating the highest degree of particle packing and more mass per unit volume. The value of this property is to increase the gravitational settling rate in the time of transport, which could benefit in propping in the fractures, specifically in the system of slickwater or low-viscosity fluids (Duenckel et al. 2017). According to results, a higher bulk density of proppant can enhance the fracture conductivity because it can create more proppant mass per unit volume and be more resistant to compaction during the shut-in stress. However, the high values of bulk density may have an unwanted impact by imposing an extra burden on the surface equipment and increasing the pumping demand. This highlights the importance of a balancing setup that should take into account the aspects of proppant density, transport behavior, and configuration of the wellbore. Practically, high-stress reservoirs are preferably supported by proppant with moderate-high bulk density, while lighter ones are better in situations with longer distances of transportation or the cases of vertical placement (Liang et al. 2016).

S4 showed the minimum value of bulk density at 0.91 gr/cc, representing a more porous packing or less particle mass. This feature could undermine its settling and transport facilities. To be used ideally in deep or deviated wells, these materials may require higher-variety fluids or much-regulated pumping procedures (Palisch et al., 2010). Moreover, it is possible to improve bulk density once resin is introduced into quartz sand particles, whereby the resin adds mass to the particles and the pores are filled with a more dense medium. These results indicate why maximizing bulk density during proppant design is important. Although increased densities enhance better conductivity and stress-related stability, they should be well-regulated to prevent inefficiency in operations. Future investigations need to be conducted to enhance the balance between bulk density and fracture performance and transport efficiency. This will ensure dependable and effective proppant placement at various reservoir conditions to create a balance between bulk density and fracture performance and transport efficiency.

Turbidity

The turbidity values of the four analyzed proppant samples are summarized in Table 8.

Table 8. Turbidity test results

Turbidity Test Results			
No	Sample	Mark	unit
1	S1	56	NTU
2	S2	1	NTU
3	S3	1	NTU
4	S4	1	NTU

According to API 19C standards, the turbidity of proppant material should not be more than 250 NTU. This criterion is achieved in all samples tested, but S1 differs significantly from S2, S3, and S4. In particular, S1, which has a turbidity of 56 NTU, is clearly below the threshold tops. However, there is a powerful indication that the suspended sediment concentration in S1 is much higher than the others, which reported 1 NTU of turbidity each. S1 probably has higher fines or washable impurities, which can be mobilized when subjected to hydraulic fracturing and might reach the formation. These contaminants can lead to pore-clogging, formation harm, as well as reduced proppant-pack permeability, particularly in the closure-stress high-temperature regimes (Palisch et al., 2010). In contrast, the low turbidity of Samples S2 to S4 shows a high level of cleanliness, promoting their capacity to maintain fracture conductivity and minimizing the formation of near-fractures. The samples meet the API minimum standards concerning the baseline API requirements. However, special consideration should be taken when requiring the samples in tight formations or sensitive sandstone reservoirs due to the high turbidity recorded on the samples S1. In these settings, any degree of contamination might cause severe permeation damage. To target this risk, it can be recommended that these samples be pre-treated, such as by washing or chemical cleaning, before they are applied in the field (Duenckel et al. 2017).

Low-turbidity proppant is also ideal in formations with high permeability or water sensitivity because these materials will minimize the introduction of particles that will cause damage. Due to its effect on the improvement of fracture conductivity, Cipolla (2009) reported that an increase in the quality of proppant, specifically with regard to the clean properties and optimum size distribution. This can be used to ensure that the recovery of hydrocarbons is sustained over the lifespan of the well being used to produce the hydrocarbons.

Acid solubility

The results of the acid solubility test obtained in this study are in Table 7.

Table 9. Acid Solubility Test Results

Acid solubility test results			
No	Sample	Mark	unit
1	S1	12	%
2	S2	16	%
3	S3	4	%
4	S4	2	%

Acid solubility is essential in determining the chemical strength of a proppant under acidic conditions used in a downhole environment. Depending on API 19C recommendations, proppant materials should be restricted to specific acid solubility rates to resist the corrosive nature of the stimulation fluids, such as hydrochloric or hydrofluoric acid. In the case of sand proppant, the maximum solubility permitted is not to exceed 8.0 wt%, equivalent to 20/40 mesh dimensions and below grades, and 6.0 wt%, equivalent to the highest grades (Edition et al. 2008).

The testing results indicate that exclusively Samples S3 (4%) and S4 (2%) are below those maximum solubility levels (<=8 %) and provide a powerful chemical resistance in acidic conditions. Samples S1 (12%) and S2 (16%), on the other hand, exceed these values, implying that a higher concentration of acid-reactive minerals, including carbonates and feldspars, cannot resist acids. Proppant with a higher acid solubility potentially causes structural dilution, creation of fines, and low conductivity of the fractures. It has been shown that high silica content and a reduced amount of impurities demonstrate an increased resistance to acid-induced degradation in proppant. Moreover, overly soluble might lead to structural failure and pore cementation through acid stimulation (Ramazanov et al. 2024). Therefore, Samples S3 and S4 are well-suited for use in acid-stimulated reservoirs due to their strong chemical resistance. In contrast, Samples S1 and S2 may compromise the long-term performance of fractures, posing a risk under such conditions.

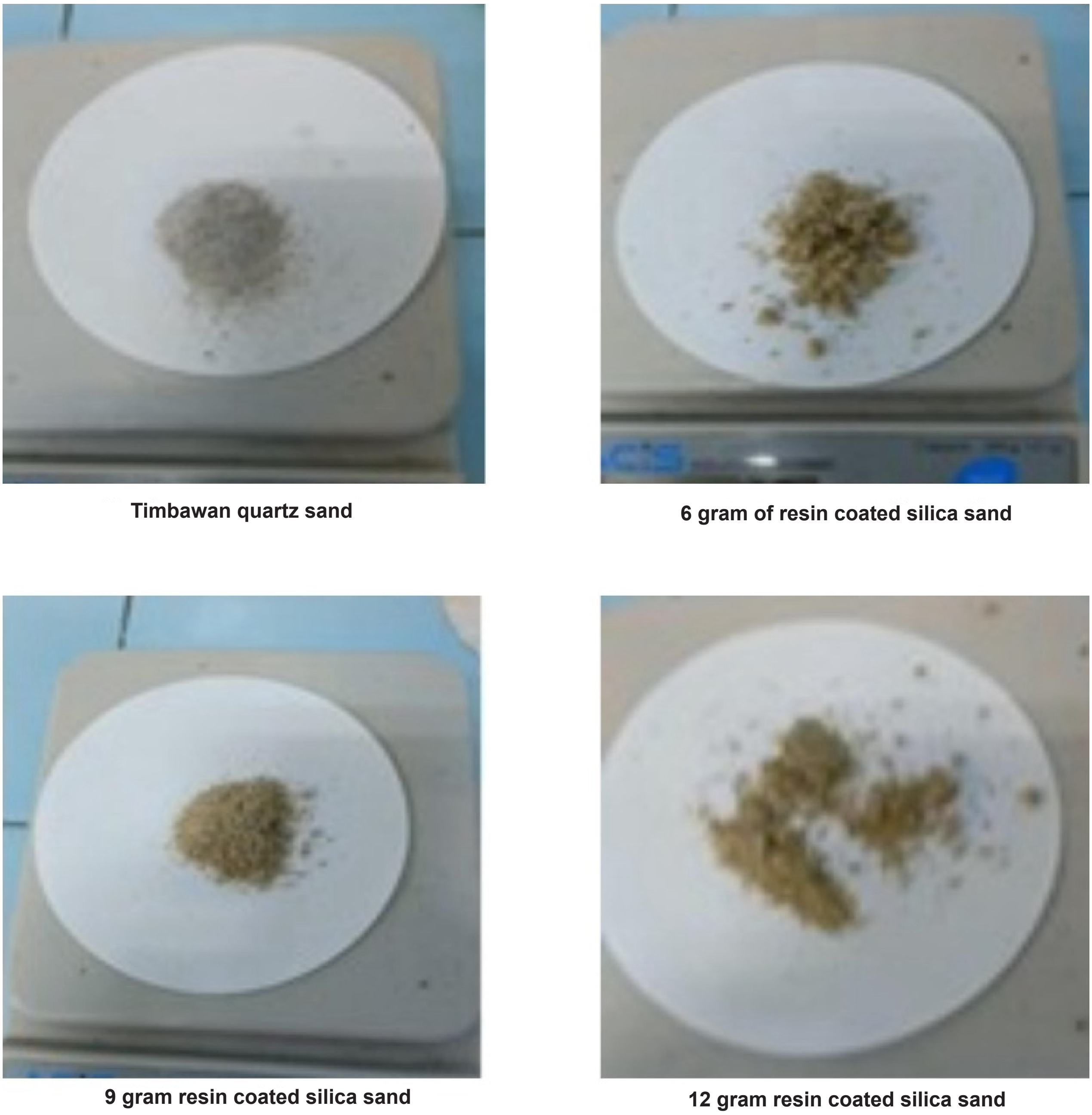

Figure 13. Acid Slubility Test Result of Tibawab Quartz Sand and Resin-Coated Silica Sand at Different Resin Weights (6 g, 9 g, and 12 g)

Crush resistance test

Crush resistance is a key parameter in the determination of the durability and conductivity of proppant in hydraulic fractures, particularly under elevated closure stress conditions. By using API 19C standards, 4 proppant samples (S1–S4) underwent crush testing at 2000, 5000, 6000, and 7000 psi closure stresses. The post-test percentage of fines produced by each sample is summarized in Table 10.

This information provides an overview of the mechanical stability of the tested proppant and its appropriateness to sustain the performance of fractures during the life of the hydraulic stimulation procedures. The information above supports the importance of proppant choice to maximize long-term fracture conductivity and reservoir productivity, with high crush resistance.

Table 10. Crush resistance test result

Crush Resistance Test Result					
No	**Sample**	**2000 PSI**	**5000 PSI**	**6000 PSI**	**7000 PSI**
1	S1	25.35%			
2	S2		10%	11.86%	12.42%
3	S3		4.81%	5.73%	7.80%
4	S4		3.74%	5.03%	6.05%

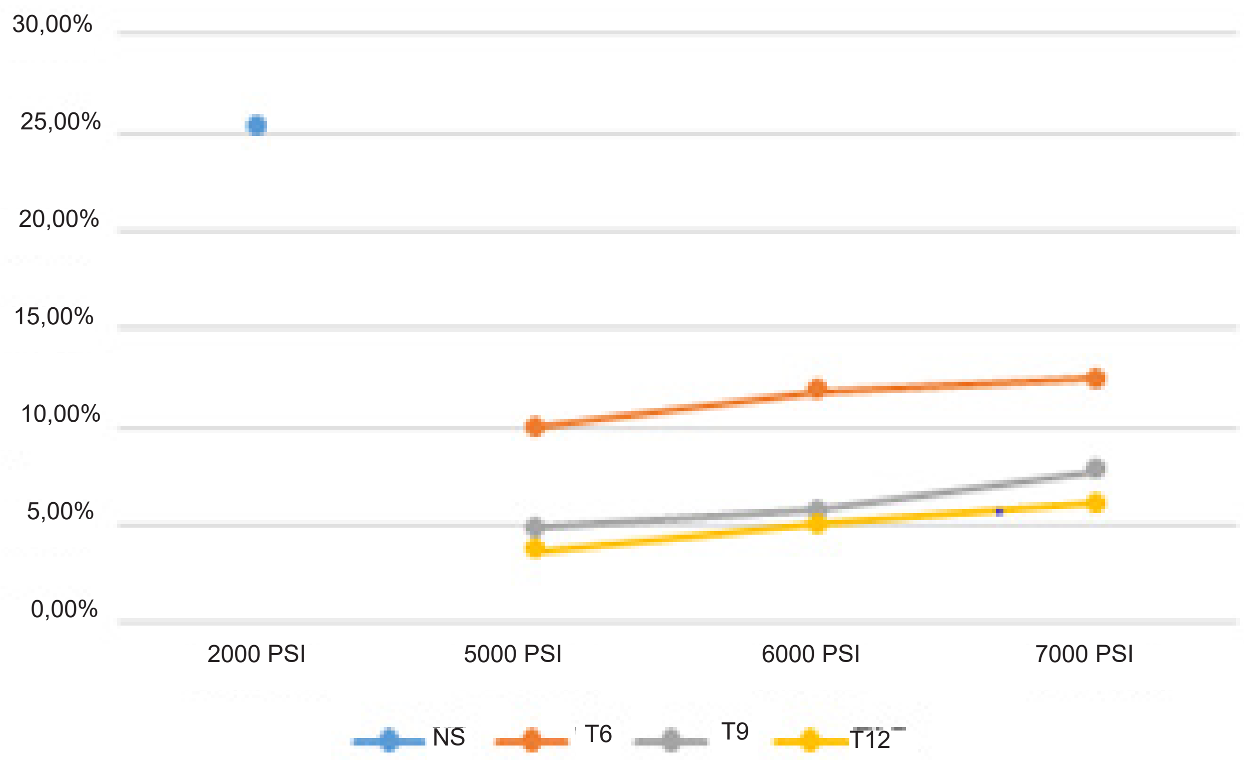

Figure 14. Crush resistance test results

S1 produced 25.35% of fines with the recorded stress of 2000 psi, well above the API 19C limit of 10%. This high-level failure under low pressures indicates poor structural quality, which makes S1 inapplicable in moderate-high pressures for use in hydraulic fracturing. Lack of such data at higher pressures is probably a result of having such a sample discarded early because of the low performance.

S2, S3, and S4 had better mechanical properties, particularly in elevated closure stresses. Samples S4 showed the most superior results, and had the lowest percentage of fines at 5000 psi and 3.74, and at 7000 psi, and increased modestly to 6.05. This excellent crush strength proves that S4 can be used in high-pressure formations since it shows few stress degradations.

On the same note, S3 generated fines far below the API 19C guideline of approximately 6000 psi, with values of 4.81% and 5.73% recorded at 5000 and 6000 psi, respectively. Despite the control sample of 30K being 0.077% over the target value of 10% 7.80%, the 7000 psi sample still displayed excellent mechanical stability results relative to other proppants found in literature (Liang et al. 2016; Palisch et al. 2010).

S2 showed a steadily decreasing mechanical integrity as it produced 10.00% fines at 5000 psi (which met the API limit) and more than that at 6000 psi (11.86 percent) and 7000 psi (12.42 percent). This test implies that although S2 can be suitable in low-stress environments, it is not suitable in high-stress environments, such as deep completions. The findings are consistent with observations made by Blauch (1999), who reported that increased fines production resulting from proppant crushing reduces proppant pack permeability, obstructs flow pathways, and promotes particle embedment.

According to API 19C, proppant can have no more than 10% fines on the specified closure stresses to be eligible for application in hydraulic fracturing. According to these requirements, samples S4 and S3 perform to the mechanical strength requirements, and the former sample of approximately 6000 psi. S2 tends to fail slightly at greater stresses, and S1 is quite unsuitable for hydraulic fracturing purposes. S4, in turn, appears as the best fit applied to high-pressure conditions, delivering better resistance to degradation caused by stress and fulfilling the industry's standards.

CONCLUSION

In conclusion, this study showed that quartz sand of Tibawan, Rokan Hulu sand, coated with 12 grams of epoxy resin (S4), corresponds to API 19C standards and hence has good potential as a proppant material in the oil and gas industries. Tests of critical properties, such as roughness, sphericity, turbidity, bulk density, acid solubility, and crush resistance, showed considerable gains after the epoxy resin covering procedure. The successful performance of S4, which meets API 19C requirements, demonstrated the effectiveness of resin coating in enhancing the properties of locally sourced quartz sand as a proppant. Based on these results, further investigation is recommended to optimize the coating technique and conduct industrial-scale testing to validate the performance and long-term applicability in petroleum operations.

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GLOSSARY OF TERMS

Symbol	Definition	Unit
Al_2O_3	Aluminum Oxide	
API	American Petroleum Institute	
C	Carbon	
CaO	Calcium Oxide	
CNTs	Carbon nanotubes	
HCL	*Hydrogen Clorida*	
HF	*Hydrogen Fluorida*	
ISO	*International Standar Organization*	
Na_2O	Sodium Oxide	
NTU	*Nephelometric Turbidity Unit*	
PHEA	Poly(2-hydroxyethyl acrylate)	
PP	Polypropylene	
PS	Polystyrene	
SiO_2	Silicon Dioxide	

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